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A review on hydropower plant models and control

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Abstract

The recent increased number of black outs in the power system has been largely due to growing competition and deregulation among the power industry. Power systems are complex nonlinear systems and often exhibit low frequency electro-mechanical oscillations due to insufficient damping caused by severe operating conditions. This needs an advanced modeling and control techniques for effective control of power plants. In case of hydroelectric plant the hydro turbine is a non-linear, non-stationary multivariable system whose characteristics vary significantly with the unpredictable load on it and this presents a difficulty in designing an efficient and reliable controller. A conservatively designed control fails to perform as expected. Keeping this in mind, hydro plant control is an application area with an interesting set of problems for control engineering people. Mainly some of these problems focus towards regulation of turbine with large load variation in the power system. These problems have not been adequately solved and continue to pose challenges to the control community. In this review paper, the authors have tried to broadly categorize the research work done so far on the basis of hydro plant model development and its controller design under different sections. A substantial number of relevant research papers can be found on the plant modeling, design aspects of control methodologies and their performance study.

Keywords: Hydroturbine; Nonlinear; Control approach; Modeling

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Contents

1. Introduction

The large diversification in behavior of nonlinear plants across its operating points requires different control objectives and thus different control actions to be taken for each variation in operating point. The nonlinear dynamic characteristics of hydro plant largely depend on internal and external disturbances, set point changes, leading to shift from its optimum operating point. The schematic of hydropower plant is illustrated in Fig. 1. A key item of any hydro power plant is the governor. This governing system provides a means of controlling power and frequency. The speed governor includes all those elements, which are directly responsive to speed and position or influence the action of other elements of the speed governing system. The speed control mechanism includes equipment such as relays, servomotors, pressure or power amplifying devices, levers and linkages between the speed governor and governor-controlled gates/vanes. The speed governor normally actuates the governor-controlled gates/vanes that regulate the water input to the turbine through the speed control mechanism.

Conventionally, hydraulic-mechanical governor and electro-hydraulic type with PID controllers are popular in use. The technologies of these governors have developed considerably over the past years. In recent years, digital governors have gradually replaced these analog controllers. Recent developments in the field of control technologies impose a new approach in the turbine control systems with application of artificial intelligence (AI). One of the most discussed applications of artificial intelligence in turbine governing is the replacement of a standard Electro-hydraulic governor with fuzzy logic or neural network or hybrid controller-fuzzy logic and neural network.

The turbine model considered in the design of the governor plays an important role. A great deal of attention has been done towards linearized modeling. A linear model

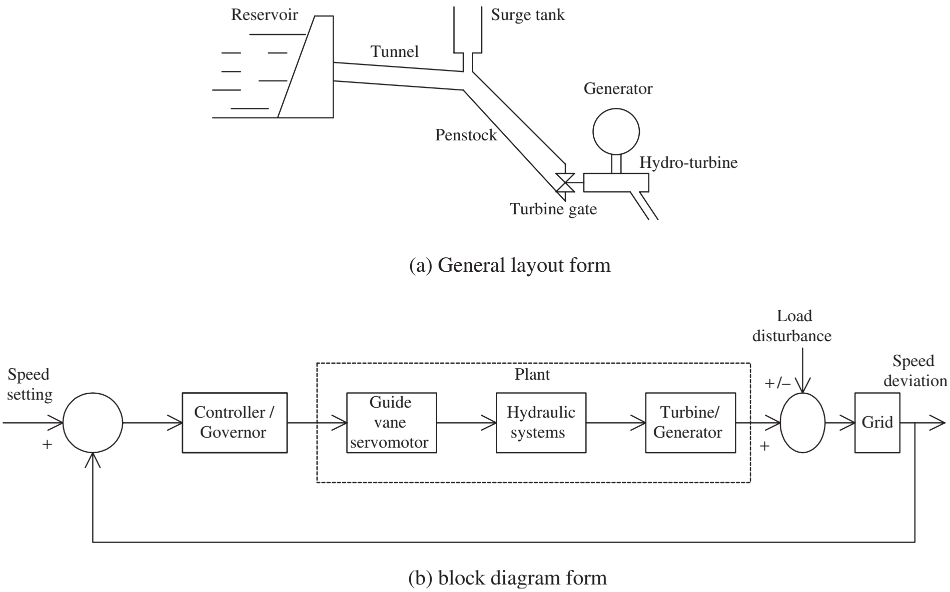

Fig. 1. Schematic of hydropower plant with its structures and components (a) general layout form (b) block diagram form

representation of the turbine system is important in governor tuning using classical techniques (frequency response, root locus, etc.), which is valid only for small signal performance study (load disturbance $< \pm 10\%$ rated value or frequency deviation $< \pm 1\%$ rated value). This makes model an over simplified and realistic issues not being discussed. Such a linearized model is inadequate for large variations in power output ($> \pm 25\%$ rated load) and frequency study ($> \pm 8\%$ rated value) [1]. As the hydraulic turbine exhibits highly nonlinear characteristics that vary significantly with the unpredictable load on the unit, this requires controller gain scheduling at different gate positions and speed error. In practice they are designed on a linearized turbine model at rated condition, the controller is then de-tuned for worst operating conditions. Such a design approach does not perform optimally. Nonlinear models are required when speed and power changes are large during an islanding, load rejection and system restoration conditions. A nonlinear model should include the effect of water compressibility i.e. inclusion of transmission-line-like reflections which occur in the elastic-walled pipe carrying compressible fluid. [2]. This modeling is more important in a system with long penstock. An interesting area for control theory and application is in the study of a penstock-turbine model with elastic water column effect. To gain economic merits, determination of transfer function limits and operating limits has gained an importance in recent years, specially, in case of common penstock model. A hydraulic coupling gets introduced between the units of the plant [3,4].

This gives an opportunity to investigate models of the hydro plant and turbine control existing in different plant layout/configurations.

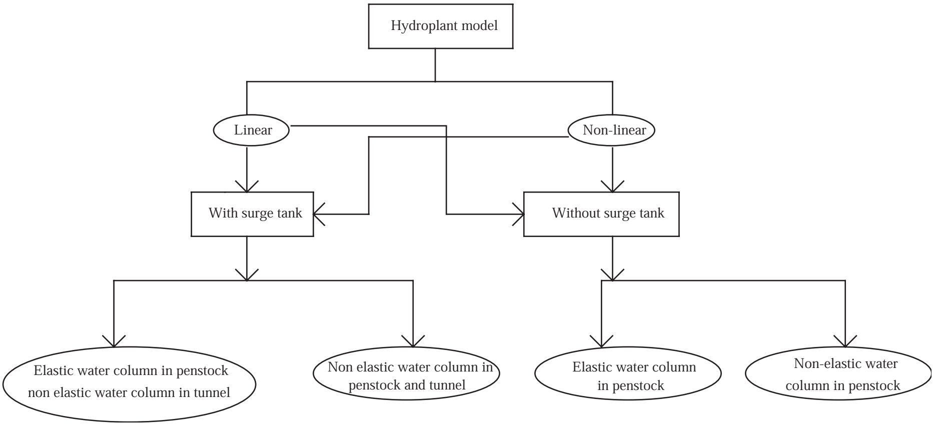

Fig. 2. Overview of hydropower plant models

2. An overview

2.1. Hydroplant models

Fig. 2 presents an overview of hydropower plant models used in study. The hydro plant models may be classified in broad sense as: the linear (non-elastic) models and nonlinear (elastic) models. This classification is based on the complexity of equations involved in the modeling. The former model uses equations linearized at an operating point. And the latter model incorporates nonlinear equations of the (i) mechanical power; and (ii) the relationship between the turbine flow, the turbine head and the gate opening.

These are further sub-classified as with and without surge tank effects. Again they are categorized as (i) an elastic water column in the penstock and a non-elastic water column in the tunnel and (ii) non-elastic water column. Linearized models are used in the study of control system stability or small signal stability.

2.1.1. Model with non-elastic water column effect

A simple linearized model gives an efficient computation of the transient response for specific controller settings. This representation is based on the following assumptions:

- Negligible hydraulic resistance;
- Inelastic penstock wall and incompressible water flow;
- Velocity of water proportional to gate position;
- Turbine output proportional to the product of head and volume flow.

The linearized transfer function relating the incremental torque to the gate deviation is given as [5]:

$$\frac{\Delta P_m(s)}{\Delta Z(s)} = \frac{(1 - sT_w)}{(1 + s0.5T_w)}$$

In most of the literature investigated, simple first order models have been considered in study. It is to be argued here that a model for long length penstock represented as first

order model will have significant error. Thus a transient behavior analysis by first order model may be satisfactory however it may not represent accurate response. Hence accuracy must not be compromised for the sake of model simplicity.

2.1.2. Model with elastic water column effect

In many applications a detailed hydraulic system model is required to take into consideration the compressibility property of water and elastic property of penstock. This behavior represents a dynamic interaction between the hydraulic system and electrical system. Pressure wave in the penstock represents a hydraulic transmission line terminated by an open circuit at the turbine and a short circuit at the reservoir [6–9]. The transfer function relating the incremental head and flow can be rewritten as:

$$\frac{H(s)}{Q(s)} = -\frac{T_{\mathrm{w}}}{T_{\mathrm{e}}}\tanh\left(sT_e + F\right)$$

where,

F	friction loss in hydraulic structure
$H(S)$	Laplace transform of incremental head
$Q(S)$	Laplace transform of incremental flow
T_{e}	Travel time

The transfer function between the incremental torque to changes in guide vane position with elastic water column effect is given as [3,6–9]:

$$\frac{\Delta P_{\mathrm{m}}(s)}{\Delta Z(s)} = \frac{a_{23} + (a_{11}a_{23} - a_{21}a_{13})\frac{T_{\mathrm{w}}}{T_{\mathrm{e}}}\tanh\left(sT_{\mathrm{e}} + F\right)}{1 + a_{11}\frac{T_{\mathrm{w}}}{T_{\mathrm{e}}}\tanh\left(sT_{\mathrm{e}} + F\right)}$$

The parameters a_{ij} are the partial derivatives of flow and torque with respect to head, speed and guide vane position respectively. The above equation is a distributed parameter model and it is difficult to have its use in system stabilities study.

2.2. Governor

2.2.1. Control objective

A prerequisite to any control system design is the specification of the design objectives. In order to design and then assess the performance of a control system, criteria must be laid by which the quality of control can be judged. Any control system needs to be analyzed for its performance. The types of speed controller are discussed in brief in following section.

2.2.2. Hydraulic-mechanical governor

The governing function realized in such governors is with the use of mechanical and hydraulic components. The permanent droop determines the speed regulation under steady state conditions. For stable operation of the governor, large temporary droop compensation is included. This is provided by incorporation of dashpot. This can also be

bypassed if desired. Transient droop compensation is given by [10]:

$$G_c(s) = \frac{(1 + sT_R)}{\{1 + (R_T/R_p)sT_R\}}$$

where,

T_R	reset time or dashpot constant
R_T	temporary droop
R_p	permanent droop

For stable operation under islanding conditions, the optimum choice of the temporary droop R_T and reset time T_R is given by [10]:

$$R_T = [2.3 - (T_w - 1.0)\,0.15]\,\frac{T_w}{T_M}$$

$$T_R = [5.0 - (T_w - 1.0)\,0.5]T_w$$

2.2.3. Electro-hydraulic governor with PID-controller

The classical PID is the most common form of controller used in governing. The structure of the PID controller is simple. The three terms of the controller treat the current control error (P), past control error (I), and predicted future control error (D). Its use ensures faster speed response by providing both transient gain reduction/transient gain increase. The derivative term in the control action is important in case of isolated operation. Its use results in excessive oscillation in interconnected system. The transfer function of PID without derivative effect in action is equivalent to that of the hydraulic-mechanical governor. The design is based on linear control theory at one load condition and then de-tuned for worst operating conditions. This controller design does not guarantee the close loop system to remain stable at all operating conditions.

2.2.4. Digital governor

Advancement in digital technology has resulted in tremendous reduction in digital component's cost and improvement in reliability. This in turn has led to researchers for an alternative to analog circuitry PI (or PID) controlled governor. A digital governor can be designed to offer:

- Speed control of the turbine;
- Operate sensitively and respond to errors $\pm$ 0.15 Hz to restore the normal condition;
- Parallel operation in multi-machine system;
- A minimum dead band;
- Good dynamic response on load throw-off and during static frequency condition.
- Steep droop characteristics;
- Control of load based on load reference and line frequency using feed back control loops;
- A self-regulating feature to stabilize the system.

Also these are multi-channeled so as to operate in integrated control of the turbine-generating set [11]. It uses optimal gain values for each point of desired operation stored in memory. The controller then updates the gain in the control algorithm to reflect changes in the operating point. Computer programs are used to generate and implement variable gains.

The need for improvement in reliability and redundancy led to development of a duplicate microprocessor based governor [12]. Because of the fast start-up and synchronization, the no-load operation and the no-load flow loss decreases.

3. Research review

The research work carried out so far in the field of hydro plant is so vast that it is quite difficult for one to comprehensively review the literature covering all aspects of its modeling, operation and control in various configurations. This section of the paper presents a brief literature review of previous works related to topics within modeling and control of hydro power plant.

3.1. Hydroplant models

A number of configurations of hydro plant model exist depending upon each requirement involved in study. An essential component of effective control system design is appropriate modeling of the plant dynamics. The models are required to be as simple as possible while retaining all significant dynamic characteristics. There exist many research publications in which the modeling of hydro plant and its controller design have been discussed. The contribution by Oldenburger et al. [13] is important in modeling point of view. The study presented includes elastic water effects, though the nonlinear dynamics is linearized at an operating point. Undrill et al. [14] have determined the procedure for computation of temporary droop. IEEE working group/committee [15,16] have reported various models of hydro plant and techniques to control the power generation. Various linear and nonlinear with non-elastic and elastic water column effects are discussed. Ramey et al. [2], Luqing et al. [17], Wozniak [18], Malik et al. [19] have considered an ideal and non-elastic water column in their study. A classical linearized turbine model at an operating point has been mentioned.

An approximation of hydro turbine transfer function to a second order for multimachine stability studies is described in [20]. Similarly, Sanathanan [9] too has proposed a method to derive a reduced order model for hydro turbines in case of long penstock. The author demonstrates an inefficient representation of turbine characteristics with first order linear model for such a system. Though the first order model shows a stable and strongly damped transient response, however the real plant presents an unsatisfactory oscillations. While with a second order model, a good approximation is shown. Kundur [21] has considered the dynamics of elastic water column effect as nonlinear in modeling of plant. Fangtong et al. [22] considered plant identification and parameter estimation techniques for modeling of hydro turbine-generating set to design a governing system. Open- and closed-loop identification of hydro turbine using recursive least square estimation algorithm is discussed. Qijuan et al. [23] introduced the dynamic modeling of hydro turbine-generating set as a single machine with local load using recursive least square estimation algorithm. Also a neural network structure 3-2-1 using prediction

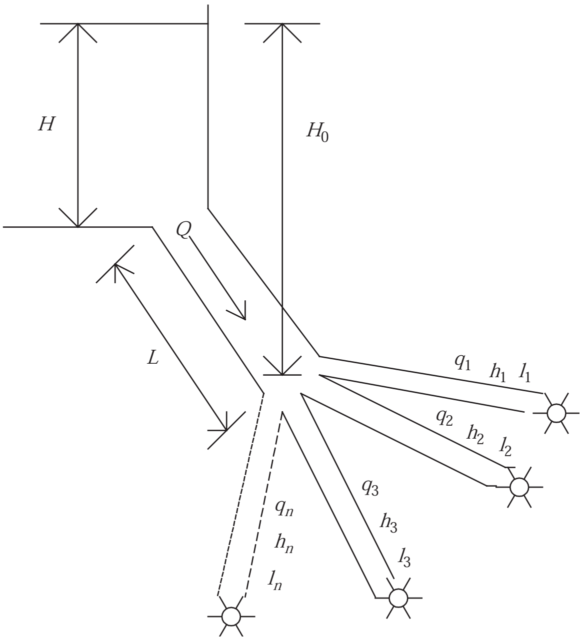

Fig. 3. Hydraulically coupled turbines in a power plant

error-learning algorithm is presented for modeling. Chang et al. [24] described the nonlinear simulation of hydro turbine governing system based on neural network. Two three-layered perceptron neural network NN1 and NN2 having structure 1-4-1 and 2-12-2 are considered in study. The former structure forms a nonlinear relation between servomotor stroke and guide vane opening while later structure between guide vane, speed, efficiency and discharge.

The hydro plant with turbines sharing a common penstock has been discussed in some literatures [25–29]. Fig. 3 shows a hydro plant with turbines hydraulically coupled through a common penstock. Vournas et al. [25] have developed transfer function for hydraulic turbines sharing a common penstock. Both non-elastic and elastic model of penstock has been considered. In a similar work, Hannet et al. [26] and Jaeger et al. [27] too have discussed the same development of the model based on field tests. In another work, Hannet et al. [28] has demonstrated the coupling effect on parameter settings of hydraulic-mechanical governor under islanding or black start conditions. The nonlinear dynamics in a cascaded hydro plant model is described in [29].

Sourza et al. [30] describes the hydraulic transients for nonlinear hydraulic structures and turbine based on analog mathematical models of transient phenomenon equations.

Most of the authors have not considered the comprehensive investigation that includes the dynamics of compressible and elastic effect in long penstock. These effects represent a delay e^{-2sT_e}, which is irrational term in the hydraulic structure. A transfer function with irrational term is difficult to solve and sometimes cannot be used directly in stability studies. The study made for relatively long penstock on the basis of non-elastic water column effect will have significant error. Such approach in the governor design

downgrades its effectiveness. The approximation of a high order system by a low order seeks importance particularly in the controller design and control system analysis. A simple model involves less computation time of the transient response. Thus for designing efficient control system, it becomes necessary to use reduced order turbine-penstock model with elastic water column effect of a long penstock in hydropower plant.

3.2. Plant (speed/frequency) controllers

As discussed in Section 2.2, the main objective of speed controller is to regulate the turbine-generat speed and hence the frequency and the active power in response to load variation. The classical control theory concerned with single input and single output (SISO) is mainly based on Laplace transforms theory. In this, time response is tested with standard signals such as step and impulse. Bode, Nicholas and Nyquist plots describe the characteristic features of the test system in frequency domain. While modern control theory is based on the description of system equation in terms of n first-order differential equations, which may be combined into a first-order vector-matrix differential equation. The stability is analyzed by the controllability and observability test. The developments of controllers for hydro turbine as according to control approaches applied are reviewed in the followings.

3.2.1. Controllers for linear models

3.2.1.1. Classical approach. The early papers Paynter [31], Hovey [5] Leum [32] are important in emphasizing the need to understand the design of control action. These literatures contributed towards establishing general guidelines for the selection of control parameters. Paynter in his work has studied the performance of a simple governor on an analog computer without considering the permanent droop and the generator damping in study. Later Hovey verified the stability region mathematically as described by Paynter along with the approach of practical power system in his analysis. These two authors neglected the steady state speed droop, net damping torque and mechanical inertia of the rotating mass.

However, Chaudhry [33] took into account the permanent speed droop and the generator damping, and used the Routh-Hurwitz stability criterion to extend the stability boundaries. His results have formulated a basis for governor design and it's tuning. The study for Francis turbine is described in [34].

Hagihara et al. [35] established the stability boundaries of turbine-generator unit having PID governor using the root locus method. In fact his work is extension of Hovey and Chaudhry. In their work however, the investigators have used simplified model of unit. Even gate dynamics have been neglected. Phi et al. [36] described the first ever-extensive analysis of stability limits in a model of turbine-generator connected to equivalent system. The study includes stability of generating unit as a function of unit steady state speed regulation, equivalent system steady state speed regulation, and turbine loading, interconnection, system damping, and proportional, integral, and derivative governor gains. A detailed PID governor model is derived to find the potentiometer settings for given overall governor gains. The results have been helpful in tuning of governor parameter and in explaining the observed unstable frequency oscillation phenomenon. In the past analog circuitry governor design, control gains were optimized for best efficiency point. This resulted into unsatisfactory transient response for the operation at points other

than designed. However, a programmable digital governor is not limited to these constraints. Digital control systems can significantly improve the response in contrast to PI or PID controlled governor. The governing of turbine through microcomputer/microprocessor is discussed in [37,38]. Murthy et al. [39] too have considered the same model in the study.

The contributions of Hagihara and Phi did not present emphasis on the implementation of variable gain in digital controller. However, Wozniak et al. [40] proposed in his work. A root locus technique is adopted in determining appropriate gains for infinite busload and resistive load. In [41,42], a double derivative control strategy is used. It is mentioned in the paper that digital controller has less phase lag than the analog even if sampling and filtering delays are considered in the simulation test. It is suggested to reduce the phase lag by decreasing sampling time. The authors compared the performance of control system with variable gain technique to conventionally followed constant gain technique. In another approach root locus-tuning technique is adopted to determine appropriate gains for each load level by Wozniak et al. [43] and Filbert et al. [44]. Computer programs calculate these variable gains. The authors study both isolated resistive and infinite busload model.

A graphical approach in tuning of PID controlled governor is described by Wozniak [18]. The author has developed a graph that can be used to predict optimum P and I gains based on four parameters; the water starting time constant, the rotor inertia, the self-regulation constants of the turbine and the load. The analysis is based on the plant pole cancellation design with a damping of 0.707 for closed loop system response.

Kamwa et al. [45] presents a transient stability program based approach to identify numerically a single-input multi-output state-space small-signal model of the open-loop system seen by the turbine governor. And the model is validated by comparing actual closed-loop response with those simulated in Matlab.

3.2.1.2. Modern approach. The modern control theory concerned with multiple inputs and multiple outputs (MIMO) is based on state variable representation in terms of a set of first order differential equations. It is more appropriate to label the term *modern control* as optimal control, nonlinear control, adaptive control, robust control and so on.

Thorne et al. [46] are the first to apply the state space representation and eigenvalue analysis to examine the effects of the governor parameters-proportional, integral gains, system damping and unit loading on the stability boundaries of single hydro unit connected to a large power systems.

Dhaliwal et al. [47] have used the state space to study the effect of derivative gain and other governor parameter on the stability of single machine supplying an isolated load. Their work also includes the significance of parameter variation on the stability of two hydroelectric plants operating in parallel. The authors have concluded that too high gain can cause the system to go unstable. In case of multi-machine system considered, a large derivative gain lowers the damping of electromechanical oscillations. The effect of variation of reset time constant and temporary droop on the stability of a multi-machine system is similar to that in isolated operation. An ideal simplified relationship between mechanical torque and gate are studied, neglecting damping torque to prime mover and generator. Taha [48] developed a digital model for eigenvalue analysis of PID speed controlled hydropower plants.

Arnautovic et al. [49] described the analytical study of Kaplan turbine for large perturbations. The mathematical modeling includes non-linearties and constraints of Kaplan unit and the corresponding governor. Authors have proposed a segment method of linearization to represent the turbine characteristics. This method for representing the turbine characteristics considerably reduces the simulation time as compared to the interpolation method. A sixth order linear model with time varying coefficients comprising the dynamics of the water flow, turbine rotation and governor are considered. The simulation results of the study closely agree with the measurements conducted in the plant.

Application of optimal control system using the multivariable system theory and linear optimal regulator concept in plant control is well established. These approaches are directed toward ensuring that the controller parameters remain optimal for a wide operating condition. It provides an alternative to classical techniques by which all the control design parameters can be determined for multi-input, multi-output systems. Optimal control allows us to design with respect to a performance index and it produces the best possible control system for a given set of performance objectives. The design of a control system must be based on minimizing a performance index. The word optimality refers to the minimization of properly defined cost.

The work presented by Clifton [50] in his study has included the modeling of optimal governor and compared its performance with low order governors when the effect of Allievi's constant $\zeta\left(= T_{\mathrm{w}}/T_{\mathrm{e}}\right)$ is less than unity. The model response is computed with a 20th order water hammer model. The author describes the improvement in performance by using a higher order governor model. In a similar work, the same author [51] described the use of optimal control theory in order to improve the quality of speed regulation, which is limited by turbine performance, rotational inertia, water hammer and power system self-regulation.

The characteristics of hydraulic turbine vary significantly with unpredicted load. Consequently governor optimized for one load point may not remain stable at other operating conditions. This requires gain scheduling as described in [52]. An optimal PID gain schedule is developed and tested. The control strategy is based on the equivalent of a double derivative error (DDE) with implementation of optimal gain. For each load point, optimal gains are found by minimizing a quadratic performance criterion, prior to controller operation. And during operation, the gain sets are switched-in depending on gate position and speed error magnitude. Such control is reported to have reduction of noise on the command signal and up to 42% faster response to power requests.

The conventional PID controlled regulator using fixed parameters do not meet the requirement of varying structure of control conditions. The variation of plant structure can be caused due to speed regulation or other control modes, system connection and type of load, open loop or closed-loop control, generation or compensation, or zero or non-zero gate opening. In [53], the authors have proposed a varying parameter controller. The control parameter optimization can be performed either off-line or on-line on the basis of identification. The extension of this work is described in [54].

Herron et al. [55] formulated an observer-based controller using all states as input. In their work, the pressure signal is used for speed control of hydrogenerator. This type of controller shows an improved transient response over its counterpart-PID controller. Also it effectively filters out the noise on the pressure signal. It is to mention here that, to implement such controller in some cases, uses of computer will facilitate in gain scheduling for changes in operating point.

Arnautovic et al. [56] for the first time in their paper have used the method of projective controls in developing design of governor for an arbitrary number of inputs and two outputs. The output signal regulates the guide vane and runner blades of Kaplan turbine. A state space method is considered for the design, based on the sub optimal regulator problem solved by using projective controls.

A scheme for operating the turbine at maximum efficiency at new load point is described by Schniter et al. [57]. Their study investigates the control of speed response in case of Kaplan turbine on load reduction. The control scheme for the efficiency based control involves two step action; in the first step the gates and blades move in opposite direction at maximum rates to reduce efficiency without any change in flow rate to the turbine and in the final stage, the gates and blades move simultaneously to restore maximum efficiency at new load point. The problem associated in their design as mentioned in the paper is that the control scheme is sensitive to quick changing partial derivatives a_{ij} along the system's trajectory. As suggested for future research work, improvement in performance can be achieved by incorporating mapping of turbine characteristics and tuning control actions based on current operating point and predicted trajectory. Also possible use of conduit pressure signal in the control actions is to be assessed.

In the state-space model for hydro turbine, use of linear quadratic controller assumes that the states can be measured. It is not feasible and practically possible to measure all states. There are number of uncertainties that the controller does not account for change of plant parameters in the design. One main source of uncertainty is the linearization of the non-linear system. Also some state variable measurements in the stochastic plant model can be so noisy that a control system based on such measurements would be unreliable.

To realize parameter optimization of control elements in PID governor, an orthogonal test approach is used in [58–61]. In the approach, control performance index is defined, which depends on control parameters K_p, K_i and K_d. Each of these parameters is considered under various levels as discrete variable. An optimization algorithm is developed to search for better control parameters in the neighboring space of the present ones. The authors mention to investigate the application of this approach in other controllers [61].

A self-tuning governor is designed and implemented for excitation or speed control in the work of Lim [62]. The author suggested to extend the control strategy for coordination of both excitation and governor control and for the stabilization of multi-machine power systems.

The application of the optimal control theory to design a supplementary excitation and governor control system is discussed by Smaili et al. [63]. The authors argue to have the use of multi-input multi-output (MIMO) techniques for the design of a controller instead of single-input single-output (SISO) technique for the excitation control loop. The design should also include the action of turbine/governor control as well in the control loop. In their approach, output power and the terminal voltage are used as output variables.

A hydroturbine governing due to inherent non-linear characteristics need to be modeled as multiplicative uncertainties, thus requiring the designer to seek a robust design. A robust control system exhibits the desired performance despite the presence of significant plant uncertainty due to parameter changes; unmodeled dynamics, unmodeled time delays, sensor noise or unpredicted disturbance inputs. Many recent control design methodologies focus on robustness—stability robustness and performance robustness in the presence of these uncertainties. The designer aims to obtain a system that performs

adequately over a large range of uncertain parameters. The designer ensures that system performance is retained in spite of model changes or uncertainties. The governor design by robust control theory means that the governor can provide satisfactory stability and optimal performance to the turbine over a wide variation of operating conditions.

In recent publications by Jiang [64], the author has contributed his study towards robust governor design. In the design, a linear model of the Kaplan turbine and generator connected to a large grid is considered. The design step includes modeling of the turbine non-linearities using uncertainty principle, development of an optimal robust governor by including these uncertainties, model order reduction and followed by verification of the model in time domain simulations. Network parameter changes and their effects were not considered in this work. Also tuning of such a reduced-order controller is not said to be an easy task.

This led to method using adaptive control. Malik et al. [65] in their paper have presented the "identify-then-control" approach of self-tuning. Such controller scheme offers on-line adjustment of controller parameters. The design also includes tracking of plant parameters as the operating parameters change, to provide optimal performance over the wide operating range. The methodology adopted is based on pole-shifting algorithm. The simulation studies include both fixed plant and variable plant parameters in the model. In the study of fixed plant simulation, penstock, servomechanism, turbine, generator, load, network, and non-linear links such as speed limit and dead band represent the model equations. The six transmission coefficients—a_{11}, a_{12}, a_{13}, a_{21}, a_{22} and a_{23} remain constant. For variable plant parameter simulation, the study discusses with the same model equations as fixed plant equations, however the transmission coefficients are taken as function of gate position varying from 43.74% to 100% load.

Researchers have recognized a novel method of developing decentralized robust control strategies in the past few decades. In the past studies the effects of load variations on the system were not considered, however the problem of robust control has taken a significant steps and complexity, necessitating the use of non-linear system models [66]. Numerous methods have been proposed for the robust control of power systems, including decentralized turbine/governor, decentralized excitation and their combination.

3.2.1.3. New approach. Lansberry et al. [67] have used genetic algorithm (GA) optimization approach for optimal governor tuning. This paper investigates the GA as one possible means of adaptively optimizing the gains of proportional-plus-integral governors. This tuning methodology is adaptive towards changing plant parameters-conduit time constant T_w and load self-regulation c. The authors have suggested randomly varying T_w or c within the specified region for the future scope of work. In a similar work, the authors have used genetic algorithm approach for PI controller tuning [68]. The designed control algorithm is proposed to be robust with respect to the plant parameter changes.

Development of the intelligent tuning of PID controller is the major theme of papers presented by Toro Yamamuto et al. [69] and by Yuan-Chu Chang et al. [70]. The former author have discussed the use of adaptive and learning control scheme, which is neural network techniques. The PID gains are tuned adaptively by fusing both self-tuning control technique and neural networks. The latter author has shown an improved dynamic performance of the intelligent PID controller over the conventional PID. The developed intelligent PID controller is based on an anthropormorphic intelligence. A human emulating intelligent PID controller is proposed in their study.

Artificial Intelligence (AI) techniques are finding increased applications in science and engineering. AI is basically embedded human intelligence into a machine so that it can think like a human being. Advanced control based on artificial intelligence is called intelligent control. Over a decade, there have been quite few papers published with application of AI techniques in hydro turbine governing. The application of AI is mentioned in: modeling of hydro turbine control system, governing tuning and as well as fault diagnosis.

Djukanovic et al. [71–73] have presented neural network (NN) coordinated control for both exciter as well as governor for low head power plant. Their design is based on self-organization and the predictive estimation capabilities of NN implemented through the cluster-wise segmented associative memory scheme [71]. The developed NN based controller whose control signals are adjusted using the on-line measurements can offer better damping effects for generator oscillations over a wide range of operating conditions than conventional controllers. To assess the dynamic performance, the result is compared with state space optimal controllers. In a similar work [72], authors have used fuzzy set theory and NN coordinated stabilizing control for the exciter and governor. The controller is said to be real time operation. In the design, for a non-linear system model, a linearised approximation is obtained for optimal linear regulators to serve as benchmark. A non-linear, multivariable control by using adaptive-network based fuzzy inference system (ANFIS) is proposed in [73]. This characteristic control in the system leads to self-learning capability of fuzzy controllers.

In [74] intelligent integral strategy is realized by fuzzy logic. The output of fuzzy logic algorithm modifies the integral gain of PID regulator. This makes the response robust and adaptive. In another work [75], a connectionist approach is applied in control of parameters using neural network.

Zhang et al. [76] presents an intelligent fuzzy PID controller for regulating the turbine. Authors have discussed fuzzy tuning method of PID controller. The designed fuzzy logic compensator (FLC) improves the performance of conventional PID controller. The fuzzy PID controller offers a self-tuned control gains with proportional, integral and derivative gains as non-linear functions of the input signals. Among the different methods available for tuning of PID controllers by means of fuzzy logic, fuzzy set point weighing (FSW) technique has been adopted. Jing et al. [77] proposed a control strategy for the regulation of a hydroelectric turbine that is achieved by using a discontinuous controller and incorporating a three-state valve and fuzzy logic.

3.2.2. Controllers for non-linear models

3.2.2.1. Classical approach. Sanathanan [8–9] has considered the study including the compressible effect of water column using frequency domain method to determine the optimum values of PID gains. A detailed penstock-turbine considering the water column compressibility (i.e. involving tanh function) is included in the model. It is shown that the governor control parameters are unsatisfactory, if these are obtained by considering an ideal and loss less turbine.

3.2.2.2. Modern approach. SUN et al. described [78] non-elastic water hammer and disturbances dynamics in their study. The proposed modeling approach is based on the linearization via state and dynamic feedback and non-linear robust control theory. Being it

a decentralized control strategy, it is advantageous to implement since all the variables can be locally measured and independent to network parameters.

Motivated by a decentralized turbine-governor control design for the damping of low frequency, inter-area oscillations in the system, Watanabe [79] has considered saturation of non-linearity in state variables for a robust state-feedback control design. This is an important consideration lacking in the work of SUN.

Chang et al. [80] have studied a non-linear simulation of governing system based on NN. In their discussion, the capability of NN to transform non-linear characteristics of governing system is aforementioned. In the model, the NNs are trained with back-propagation (BP) learning algorithm. The result obtained shows a higher efficiency in the nonlinear transform by NN.

Recent works in application of robust control, Eker [81–88] has considered a single-input multi-output (SIMO) design for nonlinear model and governor design. Several variables can be controlled through a single actuator. A multi-loop cascaded governor using polynomial H_∞ optimization is proposed for turbine speed control. Water, load disturbances and permanent oscillations in inter-area modes are included in the design along with water hammer effects, traveling waves and non-elastic penstock effects. The performance is demonstrated to be better than conventional PI and PID governor. However, the high-order robust controllers are quite complex and thus questionable in practice.

3.2.3. *Controllers on application aspects*

Wozniak [89] has analyzed the stability and performance of hydro-generator. Simulation studies have been traditionally followed neglecting water column elasticity. These dynamics greatly affect governor design and thus its response. A digital controller is proposed in [90] to damp out oscillations under large disturbance. The controller improves the oscillation in generator through the guide vane position and the runner blade position. It offers better response than conventional hydraulic-mechanical controller. In the control scheme inputs are rotor speed, plant net head, guide vane opening, runner blade position, terminal voltage and current. These input signals are on-line measured. The controller calculates mechanical and electrical torques, compares them and gives output signals to position guide and runner blade.

Jones [91] has studied the effect of multivariable control of hydro turbine. Mansoor et al. [92–95], have simulated a Dinorwig pumped storage hydro plant to analyze the effect of grid size, governor parameters on dynamic response, black-start following power failure and non-linear oscillations under certain operating conditions. The application of fuzzy logic in turbine control of the same power station is discussed in [96] while the hardware-in-the-loop simulation of the same plant is described in [97]. Jones et al. [98] have proposed specification and associated guidelines for the transient and steady-state response in frequency control mode, which can serve during design, testing and commissioning and as well as forming basis for performance study. The study for 3–4 s ahead prediction in the amount of power requirement based on the grid frequency is proposed in [99]. The authors have used predictive feedforward control to track a power target signal in part load condition. The tracking is insensitive to variation in model. However, the power station is modeled using linearized transfer function.

Simulation study for a hydrogenerator start-up and the following energization of a nuclear power station's auxiliary motors under off-nominal voltage and frequency

conditions is mentioned in [100]. The paper describes the application of electromagnetic transients program (EMTP) for the simulation and modeling of hydrogenerator. Simulated results are compared with field measurements. The verification of developed software for transient stability of the same plant with field results is presented in Dai et al. [101].

The modeling of the turbine under leakage problem, partially due to the design of turbines and ageing of the plant is described in [102]. A linear model is used for each of the components in the study. The steady-state analysis is conducted for selection of best operating point during startup/shut-down and with grid connected.

The low natural frequency fluctuations in Francis turbine occur when it operates in off-design conditions. The idea to obtain active control for the said problem is discussed in [103]. The approach is based on an external excitation with hydraulic exciter to diminish an undesired frequency component of turbine's natural excitation. An investigation in oscillatory problem of generating units equipped with Francis turbines using transfer function approach, including elastic water column is proposed in [104]. Turbine-generator torsion and hunting are considered in study and their effect on vibration is investigated.

An analytical approach in modeling of transient phenomenon in penstock, valves, surge tank and Francis turbine based on impedance method is proposed in [105,106]. The study is implemented in software "SIMSEN". The interaction between the electrical and hydraulic components is exhibited with and without coupling hydraulic and electric phenomenon. The transient study of two Francis turbines investigated with hydraulic, electrical and hydroelectric components [106] under total load rejection, earth fault, out of phase synchronization and load variation is described.

A digitally implemented control scheme based on bang–bang and speed derivative methodology for impulse turbine transients is presented in [107]. The authors in [108–109] have discussed digital simulation of Pelton turbine installed at Bradley Lake hydroelectric project. The presented control scheme ensures stability for small perturbations while it fails for large load rejections. The reason for this cause is due to inclusion of high degree non-linearities. A preliminary design for the said project is proposed in [110]. Several incidents of oscillatory instability in Alaska Railbelt power system has occurred due to high gain applied to overspeed deflector control of two Pelton turbines. To overcome this problem, a combined adaptive feedforward and feedback control has been proposed in [111]. Simulation studies conducted indicate a good performance.

4. Conclusion

The review study on the research work in the area of hydropower plant model development and its control was presented in the paper. Due to diversification in layout/configuration of hydroplant, a number of models are developed to suit the requirement of performance study in each case.

It was noted that a number of contributions exists for simple linearized first-order model of the plant. Similarly a different control approaches have been tested and implemented to study the behavior of the plant and thus its performance under different conditions.

On the other hand, the non-linear models, those are required for study of large signal transient stability in isolated hydroelectric plants, their controller tuning and long-term dynamics have not been yet comprehensively studied. Although more apparent in one or two literatures (with classical control techniques), the majority of control designs do not

account for compressible effect of water column experienced in long penstock layout of the plant.

In the last one-decade some contributions have been made to seek the advantages of artificial intelligence in modeling and control of the plant. While its application in other field of science/ engineering have been successfully explored, but in the case of hydropower plant there still exists opportunity to develop a reliable model and control design for the control engineering people.

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